

PARALLEL OPERATION OF A SYNCHRONOUS GENERATOR AND
AN INFINITELY HIGH-POWERED NETWORK WHEN DRIVEN
BY A HONNEF-GROSS WIND TURBINE

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1. The Torque-Rotation Rate Characteristics of the Wind /293**
Wheel

The characteristic AK shown in Figure 1 and published in [2] gives the variation of the torque M/M_A delivered by the wind wheel as a function of its rotation rate n/n_A assuming constant wind velocity v/v_A . Instead of the torque M and the rotation rate n , we show relative values and each one refers to the so-called "design" variable. This means that Figure 1 is valid in general and is not restricted to a special case. The "design" wind velocity v_A is specified to be 12 m/sec for reasons to be given later on. This is the wind velocity at which the efficiency of wind exploitation becomes as large as possible. The corresponding normal working point on the characteristic is indicated by B. At this point, the wind wheel delivers the "design" torque M_A at the "design" rotation rate n_A , which is

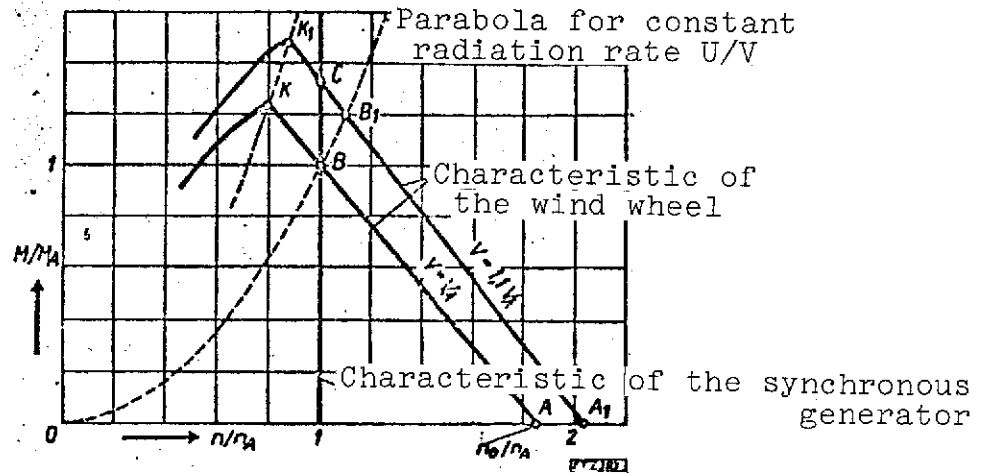
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identical with the synchronous rotation rate of the generator. When the turbine is unloaded, the rotation rate increases and takes on the value of the no load rotation rate n_0 when completely unloaded (in turbine construction, this is called the runaway rotation rate) which corresponds to the point A. According to common practice, this is assumed to be 1.85 times the design rotation rate. Of course this value also depends on the position of the "normal" working point B. When the rotation rate decreases, the torque increases further until a certain maximum value is reached (point K) specified by the flow conditions. After this, the torque decreases again with decreasing rotation rate. If the wind wheel were to drive the machine whose torque is independent of the rotation rate and if it were constant, then at the point K it would "break away" and would stand still. We would like to emphasize that such conditions do not exist at all when a synchronous generator is driven in this way. Instead, stable operational points occur along the left branch of the characteristic.

A constant wind velocity is assumed for the characteristic AK of the wind wheel, as has been mentioned many times before. When the wind velocity changes (for example, if it is increased by 10%) a new characteristic applies which is determined in the following way. First of all, an additional aerodynamic variable is required, the so-called pitch, u/v , where u is the circumferential velocity of the wind wheel and v is the wind velocity. A certain value of the pitch ratio u/v corresponds to the normal operating point B along the characteristic.

When the wind velocity is increased to $v = 1.1 v_A (= 13.2 \text{ m/sec})$, the quantity u changes for the same pitch rate and therefore for the same flow conditions. Also, the rotation rate changes by the same ratio, that is, $n = 1.1 n_A$. On the



M/M_A relative torque referred to the design torque M_A , n/n_A relative rotation rate referred to the design rotation rate n_A . $n_0 = 1.85 n_A$, no load rotation rate of the wind wheel. B — normal operational point; K — "break-away point"; A — no load point at $v = v_A$; C — operational point at $v = 1.1 v_A$.

Figure 1. Torque-rotation rate. Characteristics of the wind wheel and of the synchronous generator.

other hand, the torque increases in proportion to the square of the wind velocity, that is, $M/M_A = (v/v_A)^2$ ($= 1.21$). The working point B is displaced along a parabola to the point B of a new characteristic for $v = 1.1 v_A$. Also, each point of the original characteristic is displaced along a parabola. For example, the break-away point K is displaced to K_1 . The parabola degenerates into a straight line for the free wheeling point A, so that it changes linearly along $A_1 = 1.85 \cdot 1.1 = 2.035$. In this way, a new characteristic $A_1 K_1$ is obtained at $v = 1.1 v_A$.

2. The Torque-Rotation Rate Characteristic of the Synchronous Generator

The load point of B_1 of the new characteristic obtained from the point B is not a stable operational point, because an increased rotation rate corresponds to it. The synchronous generator is tied to a constant rotation rate $n = n_A$. This means that its characteristic is a straight line parallel to the ordinate through the point $n/n_A = 1$ (Figure 1). A stable equilibrium only occurs at the intersection point of the wind wheel characteristic and the generator characteristic, that is, at the wind velocity of $v/v_A = 1$ at the point B, and for $v/v_A = 1.1$ at the point C.

3. The Power Characteristic of the Wind Wheel

These extremely important results make it possible to determine the variation of the (relative) torque M/M_A of the wind wheel as a function of the (relative) wind velocity v/v_A using a graphical procedure for operation with a net. It is assumed that the unit operates at a constant rotation rate $n/n_A = 1$ which is synchronous with the net. In the following we will develop the equation for this torque characteristic.

The equation of a straight line through two points $B[x_1, y_1]$ and $A[x_2, y_2]$ is known from analysis. It is given by

$$y - y_1 = \frac{(y_2 - y_1)(x - x_1)}{x_2 - x_1} \quad (1)$$

If all points B, B_1, B_2, \dots , and A, A_1, A_2, \dots , are considered together, we can obtain the abscissa and ordinate values. We

found that for point B the abscissa is a linear function of the wind velocity and the ordinate is a quadratic function of the wind velocity. For point A, the ordinate has a value of 0 when there is a linear displacement of the abscissa. In this way, we find

$$\begin{aligned} x_1 &= v/v_A & x_2 &= n/n_A + v/v_A & x &= n/n_A \\ y_1 &= (v/v_A)^2 & y_2 &= 0 & y &= M/M_A \end{aligned} \quad (2)$$

This means that we have the following common equation for the wind wheel characteristic:

$$M/M_A - (v/v_A)^2 = \frac{(v/v_A)^2}{v/v_A - n/n_A + v/v_A} \cdot n/n_A - v/v_A \quad (3a)$$

After a few transformations which we will not specify here,

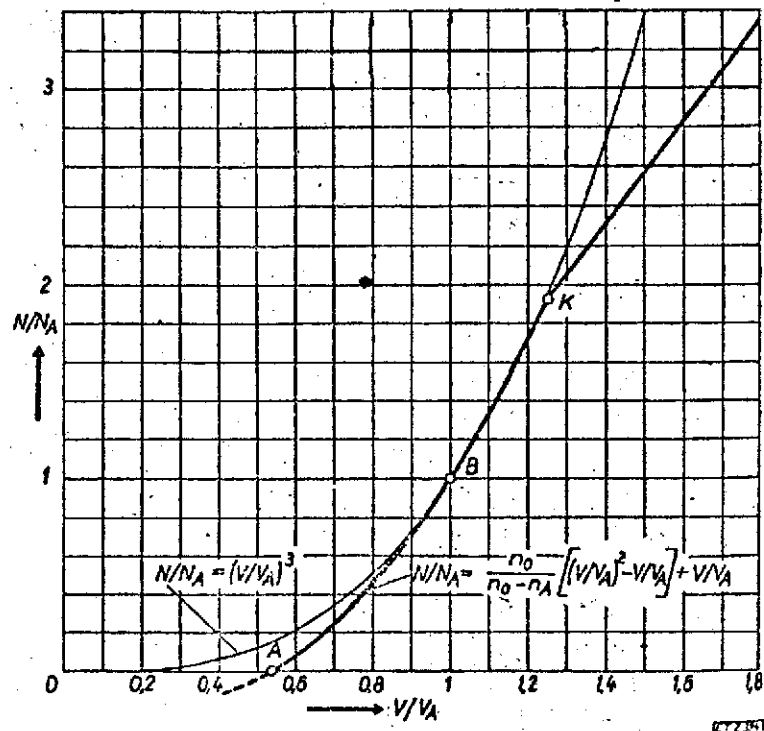
$$\begin{aligned} M/M_A &= \frac{n_A}{n_A - n_0} v/v_A + n/n_A + \frac{n_0}{n_0 - n_A} (v/v_A)^2 \\ &= \frac{n_0}{n_0 - n_A} [(v/v_A)^2 - v/v_A + n/n_A] + v/v_A + n/n_A \end{aligned} \quad (3)$$

The equation for the characteristic of the synchronous generator can be immediately given, because it is a straight line parallel to the ordinate axis

$$n/n_A = 1 \quad (4)$$

The wind wheel characteristic which specifies the torque as a function of the wind velocity is then obtained as the sum of all intersection points of the curves (3) and (4). Since the power is proportional to the product $M \cdot n$ and because the rotation rate is constant here, we can specify the (relative) power N/N_A instead of the (relative) torque. After substitution of Equation (4) in (3), we find the following extremely important wind wheel power characteristic for operation with the net:

Performance characteristics for operation alone —
 Performance characteristics for net operation —



N/N_A relative power referred to the design power level N_A , v/v_A relative wind velocity referred to the design wind velocity, $v_A = 12$ m/sec, $n_0 = 1.85 n_A$, no load rotation rate of the wind wheel.

Figure 2. Performance characteristics of the wind wheel when operated alone and with the net.

$$\left. \begin{aligned} N/N_A &= \frac{n_A}{n_A - n_0} v/v_A + \frac{n_0}{n_0 - n_A} (v/v_A)^3 \\ &= \frac{n_0}{n_0 - n_A} [(v/v_A)^3 - v/v_A] + v/v_A \end{aligned} \right\} \quad (5)$$

The power characteristic of the wind wheel when operating alone is given as follows if the wheel can move freely and is not tied to a constant rotation rate:

$$N/N_A = (v/v_A)^3. \quad (6)$$

Both power characteristics are shown in Figure 2. Corresponding to Figure 1, we have set $n_0/n_A = 1.85$, that is, $n_0/n_0 - n_A = 2.18$.

Of course Equation (5) only applies as long as Equation (3) applies, that is essentially in the region between A to K. /295

The power characteristic can be obtained graphically and analytically in the same way for the left branch of the torque-rotation rate characteristic. Again, we obtain a parabola, which is so flat that within the range under discussion, it can be considered to be a straight line with sufficient accuracy:

$$N/N_A = \frac{2.59}{v/v_A - 1.3} \quad (7)$$

4. The Nominal Power of the Synchronous Generator

The nominal power N_N of the synchronous generator can be specified completely independently of the "design" variables mentioned above. Essentially, the local wind conditions influence this quantity, i.e., the intensity and duration of the wind or the variation of the wind velocity as a function of time at the erection site of the large-scale wind generating station. Also, the planned mechanical power control system has an influence which allows the wind wheel to break away after a certain limiting wind velocity is reached. This then maintains a constant power level. This "break-away" wind velocity is specified at $v_K = 15$ m/sec.

If the wind velocity stays at or above this level, uninterrupted for at least six hours, and if this is repeated within a year and if it occurs often, the nominal power level of the generator will be specified corresponding to $v_K = 15$ m/sec. In general, the level will be between the "design" level and the "break-away" power level.

5. Operational Costs of the Synchronous Generator

a. Discussion of the power characteristics

When considering the two power characteristics in Figure 2, it can be seen that there is the smallest differences between the energy exploitation of both methods of operation, operation alone and with the net, if a working range is selected in which both characteristics coincide. The lower limit is given by $v/v_K = 0$ in a natural way. We will select the abscissa of the point K as the upper limit, where $v/v_A = 1.25$ and where the break away wind velocity is $v_K = 15$ m/sec. Of necessity, for the "normal" operational point B we find a "design" wind velocity of $v_A = 15/1.2 = 12$ m/sec. This means that the entire straight line part (the right branch) of the torque-rotation rate characteristic of the wind wheel is exploited from A to K (Figure 1). The intersection points of the curves (5) and (6) are given by

$$\begin{aligned} v/v_A = 1, \quad N/N_A = 1 \quad \text{and} \\ v/v_A = n_A/(n_0 - n_A) (= 1.18), \quad N/N_A = [n_A/(n_0 - n_A)]^2 (= 1.65) \end{aligned} \quad (8)$$

according to mathematical procedures. It is surprising that the power characteristic for net operation lie within this range (from $v = 12 - 14.1$ m/sec) and above the one for operation alone. On the other hand, we can see that curve (5) intersects the abscissa at $v/v_A = n_A/n_0 (= 1/1.85 = 0.54)$ and that the power becomes negative, i.e., the machine now absorbs energy from the net and operates like a motor, and the wind wheel delivers energy to the atmosphere and operates like a ventilator. In order to avoid this, the coupling with the network must be opened below a wind velocity of $v = 0.54 \cdot 12 = 6.5$ m/sec, assuming that no load losses of the unit are ignored. At this wind velocity, the generator has exactly the synchronous rotation rate for free wheeling conditions and is connected with the net in parallel

while satisfying the usual constraints.

b. Overloading of the synchronous generator

The power characteristic also forms the basis for determining how much the generator is overloaded when the wind velocity increases if it is delivering the nominal load to the network. In order to show this by means of an example, we will make the following assumptions:

1) the nominal power level of the generator corresponds to $v_K = 15$ m/sec;

2) unfavorable case, which never occurs in practice, in which the wind velocity suddenly changes from 15 to 25 m/sec;

3) no mechanical power controller. This means that the wind velocity is not perpendicular to the wheel surface.

The nominal load of the synchronous machine and for $v/v_A = 15/12 = 1.25$ corresponds to a (relative) power level of $N/N_A = 1.93$ according to Equation (5) or Figure 2, i.e., the nominal power N_N is 1.93 times the "design" power available at the "design" wind velocity $v_A = 12$ m/sec. Accordingly, we find that for $v/v_A = 25/12 = 2.08$ according to Equation (7), the ratio is $N/N_A = 4.08$. The generator overload which occurs is only $4.08/1.93 = 2.12$, in spite of the fact that a very large jump in the wind was assumed. It is instructive to compare this with an operation alone, where for $v/v_A = 1.25$ we find a ratio of $N/N_A = 1.95$ and for $v/v_A = 2.08$ $N/N_A = 9.04 (= 2.08^3)$, we find an overload of $9.04/1.95 = 4.63$. At this point, we can clearly see

the influence of net operation. Of course, there is no direct danger of overheating by a two-fold overload, even if we wish to assume that it is maintained for about a minute and that the generator had previously reached its permissible final temperature.

c. Equalization processes

Since the equilibrium between electromagnetic and mechanical forces is disturbed for a moment because of our assumptions, equalization processes will occur. The pole wheel will abruptly move forward and will carry out uniform rotation as well as oscillations having the instantaneous value β_p (the pendulum angle) around the new central position β_0 , which corresponds to the new load state. When the total deflection $\beta = \beta_0 + \beta_p$ exceeds the break-away limit, the machine is thrown out of step. This only occurs if the break away moment of the generator is exceeded, which nominally amounts to 2.5 times the nominal moments and, of course, can be increased by the design. These free oscillations β_p can be calculated. They are not maintained but decay in time, because their energy is used up by the heat of eddy currents in the massive pole shoes or by the heat of currents in special attenuation windings on the pole wheel. According to our assumptions, this would result in about a 2.7-fold transient overload, which occurs after about one second corresponding to an oscillation period T_0 of two seconds. It is reduced to a factor of about 2.3 (after 3 seconds) if we drop assumption 2. We also assume that the wind velocity gradually increases over two seconds. The slower the change in the wind velocity, the slower will be the short time amplitude and the later this will occur. In the limiting case of an infinitely slow increase in v , these equalizing processes will disappear altogether and we obtain the loads corresponding to the prevailing wind velocity and corresponding

to the steady state. In our example, this is about twice the nominal load.

d. The control of the field magnetic circulation
of the synchronous generator

Up to now, we assumed that the circulation through the field magnet remains constant when the wind velocity changes. The break-away power of the synchronous machine depends very greatly on the state of excitation and increases with increasing field magnet circulation. If we insure that the circulation increases with the wind velocity (approximately proportional to v), then it is impossible for the generator to get out of step. In the case of the planned Honneff-large-scale wind force electrical energy generating stations, the excitation current for the synchronous machine is drawn from excitation generators, which are driven by small auxiliary turbines.

Whenever there is a change in the wind velocity, this affects both the main and auxiliary turbines in the same way and in a desirable way. If we want to retain the assumption that these changes occur extremely rapidly, then it will be necessary to build up the entire magnetic circuit of the three-phase generator out of individual sheets, so that the magnetic field can immediately follow the change in the wind velocity. In this way, when the magnetic field is built up, the eddy currents will be produced more slowly. These eddy currents always occur in massive iron components.

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6. Mechanical Power Control of the Wind Wheel

The wind wheel wants to adjust to different rotation rates in accordance with the changing wind intensity. Nevertheless, synchronous operation of the three-phase generator is possible

if it is assumed that the machine is operating in parallel with a fixed network, which provides the synchronous conditions from the synchronizing network. The wind wheel will then operate at different pitch ratios for the different wind intensities. In the range $0.54 \leq v/v_A \leq 1.25$ it is $1.85 \geq [(u/v)/(u_A/v_A)] \geq 0.8$, where u_A/v_A is the "design" pitch ratio. The efficiency coefficient for wind exploitation which then occurs has been taken into account, because the wind wheel characteristic (Figure 1) corresponds to the torque delivered to the generator (generator input).

In order to avoid generator overload over a long period, which is not permissible because of heating, there is a mechanical power control unit in the Honnef large-scale wind generating station. The power level is held constant by tipping the main turbine and the auxiliary turbine starting at $v_K = 15$ m/sec, so that only the normal component of the wind pressure is effective. This dependence of the power on the tipping angle is not linear. Instead, there is only a small effect up to about a 30° tip angle. Above this, this effect increases. For this reason it is not at all necessary to tilt the turbine by 30° after about $v = 12$ m/sec in order to reduce the power level substantially. The control to a constant power level only occurs after about $v_K = 15$ m/sec is reached. This is done in steps of 6° each, and two seconds are required for each stage.

In the example of a wind discontinuity mentioned above from 15 to 25 m/sec over the extremely short time period of two seconds, the tipping angle of about 55° would be required. Since the turbine already has a 30° tip angle at $v_K = 15$ m/sec, it must only be tilted an additional 25° , and 4 - 8 seconds are required for this. The maximum transient load step in the generator occurs

after three seconds and is produced by the equalization process. This amounts to only 1.5 times the nominal moment, because the wind wheel has already turned by 10° after three seconds and then has an attitude of about 40° . After an additional five seconds, the unit again will operate at the nominal load level.

Summary

We have seen that it is entirely possible to operate a synchronous generator driven by a wind turbine while directly connected to a network. In spite of our assumption that an extremely large jump in the wind level occurred over a very short time (2 seconds), which probably will never happen, the generator is not thrown out of step. This is achieved by the following measures:

- 1) correct selection of the "normal" operation point (B in Figure 1) along the wind wheel characteristic at the "design" wind velocity;
- 2) control of the excitation of the synchronous machine as a function of the wind velocity;
- 3) mechanical power control by tipping the wind wheel.

The last measure also prevents the thermal overloading of the generator.

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16. Abstract By an infinite high-powered network we mean a network whose voltage is independent of the load states of the connected machines, and whose voltage amplitude and angular velocity is always the same. The three- phase generator operating in conjunction with this network must operate at a constant rotation rate, as must the wind wheel according to the number of its poles and the frequency of the network. In this article we will discuss the variation in the power output of a wind wheel for constant rotation rate as a function of wind velocity, which has not been done up to the present and which is required to evaluate the operational characteristics of a synchronous machine.					
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